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Wireless Schedulers with Future Sight via Real-Time 3D Environment Mapping

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Abstract—This paper proposes a new wireless scheduling methodology which takes advantage of future predictions of data rate for the several users competing for physical access. Based on a system which allows low-cost 3D mapping of an environment in real-time, the predictions are obtained via either low-resolution path-loss prediction given the physical structure of the surroundings or by reference to data rates achieved by previous visitors to a locality. The proportional fair scheduling (PFS) metric is extended to include measures of the future rates users may achieve, leading to a new family of schedulers. They show useful fairness improvements over PFS in exchange for a small capacity loss, and allow a number of configuration options and a range of trade-offs between fairness and capacity.

I. INTRODUCTION

The physical structure of the environment around a wireless network has for many years been used to enable ray-tracing for analysis and design, e.g. [1], [2]. But this is necessarily static and processed offline. If, instead, real-time physical structure information were made available to PHY/MAC-layer algorithms, then predictions could be made about the future performance of the system. The future track that a mobile node may follow can be approximated as a straight line extrapolated from their recent track, or by assuming the same path that previous visitors to a given location followed. Estimates of future data rates can be obtained by either low-resolution ray-tracing based on simple path-loss models for obstructions, or by storing a ‘fingerprint’ map of the area which holds the rate achieved by earlier visits to a given coordinate.

Such physical structure information can be provided by the augmented reality applications now emerging which allow the surroundings to be identified in various ways, e.g. Layar [3] and the ViewNet project [4]. In ViewNet’s system, on which this paper’s work is based, mobile operatives carry a webcam whose video stream is processed by a visual simultaneous localization and mapping (VSLAM) application to identify points-of-interest in the environment [5], [6]. Coordinates for these points are determined by multi-lateration around the camera and reference to absolute positioning systems such as GPS. Points are grouped to identify physical objects, giving a structural map of the environment. Users send their maps to a central controller which fuses them into one which is available to users who are currently present or who arrive later.

This paper will use the information about future data rates available from such systems to suggest a new wireless scheduling methodology utilizing both the past information common to existing schedulers and also the future information available from augmented reality systems like ViewNet. Such

a scheduler utilizes a class of information that is not normally available, so opening up new possibilities in scheduler design. The approach takes the scheduling metric used by the classical proportional fair scheduler (PFS), which relies on past and present data rate information, and augments it to include various measures of future data rates that users are expected to achieve. This leads to several different future-based schedulers, and they have a number of free parameters which influence their behavior and capacity–fairness tradeoffs.

The PFS has been examined in a related way in [7], where one of the schedulers used here is derived in part but in a different manner without the more general access to the scheduling metric which is the basis of this paper, and in [8] where future rates are considered on a probabilistic basis. Other predictive scheduling work includes [9] which is effectively a greedy search scheduler over some future time-slots, extended in [10] to consider the impact of re-configuring the system when the scheduler requires a change. An approach for a different family of scheduler is suggested in [11], which alters a simple scheduling metric to include future information in a way reminiscent of this paper, but for the very different metric they use, and less flexibly than here.

Section II introduces the main scheduling terminology and theory needed in Section III which sets out the theory of the future-based scheduling methodology that is the key contribution of the paper. Section IV presents numerical results showing the behavior of the various schedulers and finally Section V summarizes the paper and suggests future work.

II. CLASSICAL SCHEDULING

There are many criteria against which several competing users may be assessed to determine which should be granted access to a limited network resource (or ‘scheduled’) [12]. The two of interest here are throughput maximization (so-called ‘greedy’) scheduling as a baseline, and proportional fairness on which the new methodology presented in this paper is based.

Classical schedulers base their scheduling choices on a combination of the current and past values of data rate available to the users. If there are K simultaneously competing users in the system, and user $k = 1, 2, \dots, K$ has rate $R_k(t)$ at scheduling time t , then a scheduler assigns to each user a metric $m_k(t)$ and schedules the user $k^*(t) = \arg \max_k m_k(t)$.

A. Greedy Scheduler

A scheduler that chooses at each scheduling point the user with the highest throughput, the so-called ‘greedy’ scheduler,

is frequently used as a baseline comparison for other schedulers in wireless communication studies. The metric is simply:

$$m_k(t) = R_k(t). \quad (1)$$

Although this will maximize the throughput, it makes no particular attempt to share access to the network resource among the competing users. This question of fairness is considered in Section II-C. More sophisticated schedulers are therefore generally used.

B. Proportional Fair Scheduler

Originally described in [13], the proportional fair scheduler (PFS) began receiving attention in modern wireless studies in [14]. It grants access to the channel to the user whose prevailing channel conditions are best with respect to their average conditions. The PFS scheduling metric is:

$$m_k(t) = \frac{R_k(t)}{T_k(t)}, \quad (2)$$

where $T_k(t)$ is the exponentially-weighted average of user k 's previous throughputs:

$$T_k(t+1) = \begin{cases} (1 - 1/t_c) T_k(t) + (1/t_c) R_k(t), & k = k^* \\ (1 - 1/t_c) T_k(t), & k \neq k^*, \end{cases} \quad (3)$$

with t_c chosen to reflect the rate of change in the channel. Shorter t_c tends to make the system fairer among the K users but results in lower throughput compared to longer t_c which schedules more greedily but less fairly.

An important implication here is that the PFS, greedy scheduler, and the other classical schedulers form their metrics $m_k(t)$ based only on the current rate and past rates since this is traditionally the only information that would be available. However, ViewNet offers access to predictions of future rates, use of which is discussed in Section III.

C. Fairness

Since a user will not be able to transmit at all times with the use of a scheduler, some measure of how fairly the available resources are divided up among the users is needed. A popular measure of fairness is Jain's fairness index (JFI) [15]:

$$J(t) = \frac{\left(\sum_{k=1}^K R_k(t)\right)^2}{K \sum_{k=1}^K R_k^2(t)}. \quad (4)$$

JFI has the property, among others, that $0 \leq J \leq 1$, independently of K and the scale of $R_k(t)$.

Since there is a loosely inverse relation between fairness and capacity, in Section IV results for both quantities will be presented. To provide some means of single-metric comparison between schedulers, a synthetic combined metric will also be used. Termed here the capacity-fairness product (CFP), and 'capacity-fairness index' in [16], it will be defined as:

$$I(t) = R(t)J(t), \quad (5)$$

where $R(t)$ is some suitable measure of the rate achieved by all scheduled users at time t . In Section IV, this will be the mean

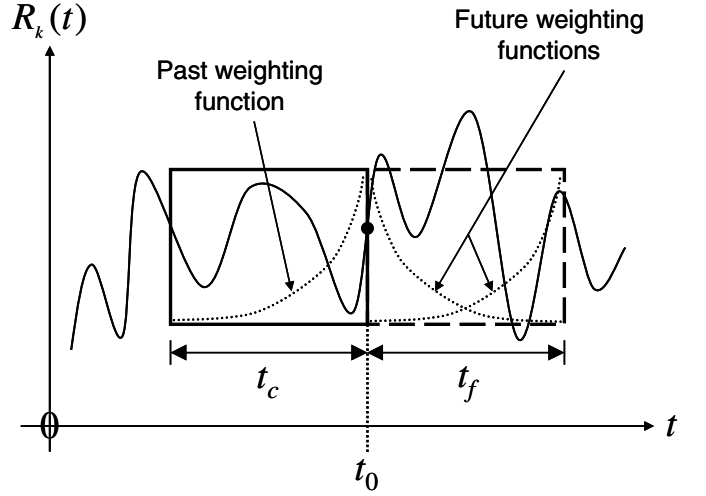


Fig. 1. Regions of the rate curve for a single user at $t = t_0$.

rate of all scheduled users in an orthogonal frequency division multiple access (OFDMA) system. The CFP nominally has units bps/Hz, but this has no particular physical meaning.

III. FUTURE-BASED SCHEDULING

The proposal in this paper is to augment the scheduling metric in order to include some form of information about the future values of rate that the users will experience. Figure 1 shows the regions of interest along a given user's rate curve assuming availability of estimates of future throughput values. The user is presently at time $t = t_0$. The exponential decay into the past informally represents the weight of the rates at times $t \leq t_0$ in the calculation of $T_k(t)$ as a result of repeated application of (3). The window into the past more accurately extends over all $0 \leq t \leq t_0$, but the window is shown bounded on the left to indicate the effect of the time scale t_c .

The idea in this paper is to add to the PFS's scheduling metric a weighted average of future throughputs in the numerator and/or denominator:

$$m_k^F(t) = \frac{\alpha R_k(t) + \gamma F_k^N(t)}{\beta T_k(t) + \delta F_k^D(t)}, \quad (6)$$

where $\alpha, \beta, \gamma, \delta$ can be any scalars and the two future-based functions $F_k^N(t)$ and $F_k^D(t)$ can be the same or different. The following possibilities are considered in this paper, where $F_k(t)$ is shorthand for either of $F_k^N(t)$ and $F_k^D(t)$. The future track of $R_k(t)$ is considered over N future scheduling points.

1) *Future weighting*: $F_k(t)$ is an exponentially-decaying weighted average forwards from t_0 , as $T_k(t)$ is backwards:

$$F_k^1(t) = (1/N) \sum_{n=1}^N (1 - 1/t_f)^n R_k(t + n). \quad (7)$$

This assigns most weight to throughputs that are in the near future and exponentially less to those further away. If $F_k^N(t) = F_k^1(t)$ (denoted 'FWN'), this function will reward high throughputs in the near term over those far away, whereas if $F_k^D(t) = F_k^1(t)$ (denoted 'FWD'), it will penalize them.

Both N and t_f are free parameters: N controls how far into the future the scheduler assigns any weight at all to R_k , and t_f is to the future what t_c is to the past. Such a formulation fits the ViewNet scenario where it may be possible to predict a user's track in the near future e.g. by extrapolating along a straight line from their recent track, but with less certainty at greater time lags. The fact that the summation is over all n in the range has the implication that the user is allowed to transmit at all scheduling times. Whilst evidently over-optimistic, all users are at least treated in the same fashion.

2) *Future sliding window*: The second proposal is to actually compute $T_k(t)$ over both the past and future windows, again with the over-optimistic assumption that user k transmits at all the N future time-slots (denoted 'TXA'). By repeated application of the $k = k^*$ portion of (3), the result is:

$$T_k(t + N) = (1 - 1/t_c)^N T_k(t) + \frac{1}{t_c} \sum_{n=1}^N (1 - 1/t_c)^{n-1} R_k(t + N - n). \quad (8)$$

This effectively has the reverse scheduling characteristics to the option discussed above, since $(1 - 1/t_c) < 1$. The expression in (8) can be viewed in the form of (6) with $\gamma = 0$:

$$\beta = \left(1 - \frac{1}{t_c}\right)^N \quad \text{and} \quad F_k^D = \frac{1}{t_c} \sum_{n=1}^N (1 - 1/t_c)^{n-1} R_k(t + N - n),$$

and α any value, which view shows that the future measure is not necessarily confined to use in the denominator of (6) and also admits an additional scalar multiplier on β if desired. This can also be combined with $F_k^N(t) = F_k^1(t)$ and $\gamma \neq 0$ from Section III-1, which will be denoted 'FWN+TXA'.

3) *Full Rescheduling over Future Window*: The final proposal is a full re-scheduling at each of the N future scheduling instants. That is, to slide the scheduler forwards, re-compute the scheduling at each slot and use this to produce, at the N^{th} scheduling slot, a new estimate for T_k which is then used directly in calculating $m_k(t)$. This avoids the 'over-optimism' of the previous two schedulers at the cost of clearly increased computational complexity. This requires no explicit future rate measure, so effectively $\gamma = \delta = 0$. This 'full future' scheduling is denoted 'FFS', and when combined with FWN in computing $m_k(t)$, 'FFS+FWN'.

IV. SIMULATION RESULTS

Results are shown in the context of a multiple-input multiple-output (MIMO) OFDMA system with the structure in Table I. A physical resource block (PRB) is a set of 16 adjacent subcarriers assigned to a single user. This groups the 768 data subcarriers into 48 PRBs. In what follows, each PRB is scheduled independently over time. The total capacity available to each user in a given PRB at time t is used as $R_k(t)$. The future information is $R_k(t + n)$ at n scheduling times into the future for the same PRB. The scheduling metrics for all users are updated at every step of t .

TABLE I
MIMO-OFDMA DOWNLINK SIMULATION PARAMETERS

Transmission Bandwidth	100 MHz
Operating Frequency	5 GHz
Subcarriers	1024
Data subcarriers	768
Guard interval length	176
Physical resource block	16 subcarriers
Transmit power	17 dBm
Antennas	4 transmit, 4 receive

All users transmit a fixed power of 17 dBm and user k experiences a received signal-to-noise ratio (SNR) based on their distance d_k from the basestation (BS) in a 100 m radius circular cell. Path loss is based on the specifications in 802.11n [17]. These stipulate free space path-loss up to a breakpoint distance d_b of 30 m and a path-loss index of 3.5 after this:

$$L_k(d_k) = \begin{cases} 46.4 + 20 \log_{10} d_k, & d_k < d_b \\ 46.4 + 20 \log_{10} d_b + 35 \log_{10} d_k/d_b, & d_k \geq d_b. \end{cases}$$

The fading channels are 3000 realizations of the ETSI BRAN 'C' model [18]. This represents a large open space (indoor or outdoor) in non-line of sight (NLOS) conditions.

A. Scheduler Characteristics

Figures 2–4 show the capacity, JFI and CFP characteristics of the eight scheduling possibilities with $t_c = t_f = N = 300$. Each is shown with five illustrative combinations of α , β , γ , δ , chosen to cover the observed differences in performance.

As would be expected, the greedy scheduler has the best capacity performance, and the others, since they are based on the PFS, have capacities in the region of that. It is apparent that there is some range of capacity performance available from the future-based schedulers, varying from 13.5 bps/Hz up to 16 bps/Hz, equivalent to the PFS. Clearly, FWN has the lowest capacity and FWN+TXA is the most sensitive to parameter changes, with $\alpha = \beta = 5$; $\gamma = \delta = 1$ giving slightly the highest capacity across the schedulers. These two schedulers both give a clear increase in JFI compared to the PFS, however, from an already-high 0.78 to 0.85–0.88 showing that addition of future rate measures to scheduling metrics is able to improve fairness over existing schedulers and maintains the significant gains of the PFS over rate-greedy scheduling. The fairness improvement using the future measure in the numerator in FWN arises since it acts to smooth out temporary dips in rate by compensating for them in the scheduling metric with near-term increases in rate. A similar benefit is seen in the FWN+TXA combination, where the sensitivity results from both the numerator and denominator of (6) being affected, whereas the other schedulers only impact one or the other.

Having future measures in the denominator of $m_k(t)$ has less impact on capacity and fairness, as seen in the values for FWD and TXA, although TXA gives marginally the higher capacity and lower fairness. Adding terms to the denominator of $m_k(t)$ does not alter the fundamental nature of the metric

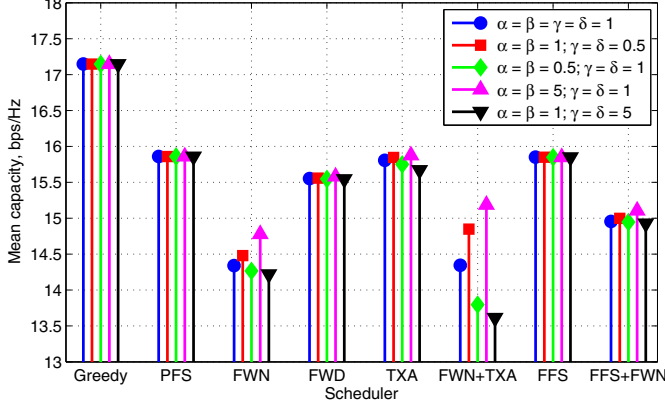


Fig. 2. Mean capacity with 6 users and $N = t_c = t_f = 300$.

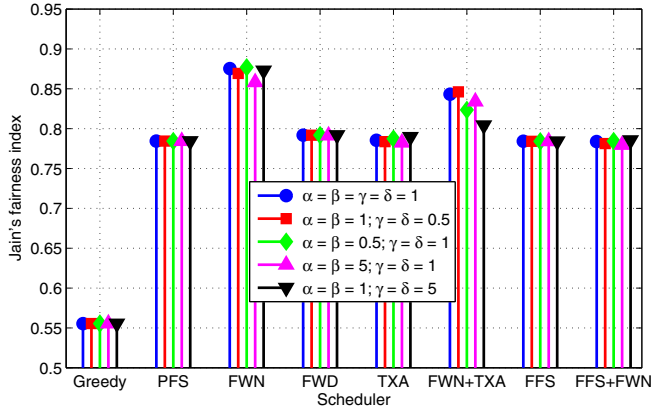


Fig. 3. JFI values with 6 users and $N = t_c = t_f = 300$.

in the way that adding to the numerator does, so the behavior of such schedulers is very similar to the PFS. The more complex ‘full-future scheduler’ has performance that matches the PFS. The main effect of FFS is to produce a longer-term average for $T_k(t)$. However, assuming that the statistics of the channel (and rate) are stationary then regardless of which sufficiently-long time window $T_k(t)$ is computed over, the statistical outcomes will be the same. This condition is clearly satisfied in these simulations, but would not be if, e.g. the users were in motion with mean path-loss changing over time.

The addition of FWN to FFS is undesirable in this scenario since it reduces capacity without any compensating increase in fairness, and thus also reduces CFP. This is due to the disruption the FWN aspect causes to the PFS-equivalent FFS in the denominator of (6): the FFS schedules forwards on the assumption that PFS scheduling decisions will be made, when in fact the decisions are based principally on FWN, and this makes the FFS prediction of $T_k(t)$ incorrect. The FFS+FWN combination thus chooses the ‘wrong’ users in some cases and capacity tends to fall.

Using CFP as an indication of the overall change to behavior between the schedulers in Fig. 4 shows that the product performance is not changed significantly across most of the

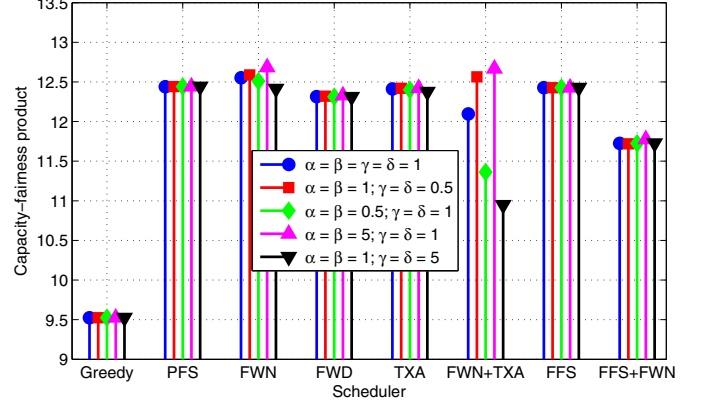


Fig. 4. CFP values with 6 users and $N = t_c = t_f = 300$.

scheduler options. This implies that the different balances in capacity and fairness apparent in Figs. 2 and 3 can be achieved with some transparency to the net tradeoff between the two. This is particularly true of FWN and FWN+TXA where the CFP is nearly the same as the other schedulers but a marked fairness increase is available.

B. Effects of System Structure and Scheduler Parameters

A number of system parameters are considered in Figs. 5–7 to see their impact on performance and behavior.

Overall, these figures confirm that the future-based schedulers behave in ways familiar from classical scheduling theory, with FWN and FWN+TXA retaining their fairness enhancements. In particular, with the addition of more users, capacity and fairness both decrease as there is increased competition for the same bandwidth and PRBs. Encouragingly, none of them show the same fairness degradation in this case as the greedy scheduler. Further, as t_c and t_f are increased, the fairness falls and capacity rises a little for the PFS and most of the future schedulers, with an overall small fall in CFP. FFS+FWN, however, shows a substantial loss in fairness as well as a 0.5 bps/Hz capacity loss and thus a CFP value some way below the other future-based schedulers. The capacity loss arises as identified previously; the fairness drop would arise anyway but is compounded by that effect, resulting in the large drop in fairness (and CFP) for the ‘10-user, 3000’ configuration.

Adjusting the future reach of the schedulers, N , while keeping the window lengths fixed gives a marginal increase in JFI and decrease in capacity which almost balance each other out in CFP. The slight JFI increase results from allowing the future schedulers to select lower-rate users ‘now’ by knowing that other users will be selected over a longer future horizon. The dip in capacity for the TXA scheduler is caused by the competing manners of those two schedulers as N grows, without the stronger, compensating effect of the t_c and t_f scheduling windows also changing.

V. SUMMARY

This paper has presented a new scheduling methodology based on access to the future data rates of users in a multi-

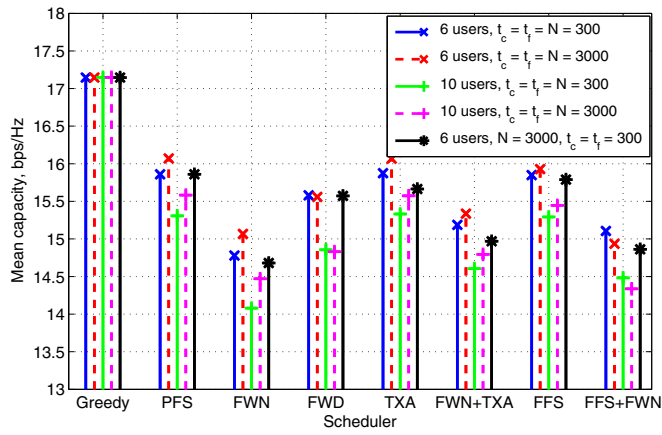


Fig. 5. Mean capacity for configuration options with $\alpha = \beta = 5$; $\gamma = \delta = 1$.

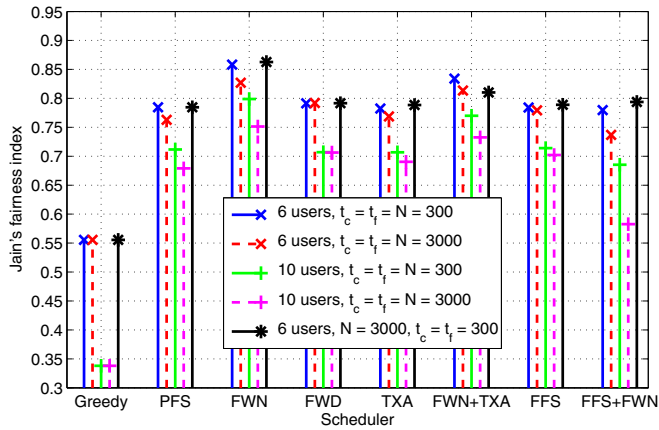


Fig. 6. JFI values for configuration options with $\alpha = \beta = 5$; $\gamma = \delta = 1$.

user scheduling problem. Based on modifying the PFS metric to include weighted measures of future rates, or by sliding the PFS forward into the future, a range of new scheduler options were introduced, and their performance and characteristics studied by simulation of a MIMO-OFDMA wireless system. It was shown that the future-based schedulers permit a number of capacity-fairness tradeoffs, with the ability in particular to improve usefully on the fairness of the classical PFS via the FWN and FWN+TXA schedulers.

With the dependence on future, and thus uncertain information, a clear avenue for further work is to include the impact of incorrect prediction on the future-based schedulers, a problem considered also in [7], [9], [11]. Within the context of the ViewNet project, since this is producing a functioning hardware system, it would be instructive to use real measurements of throughput tied to position to provide data to the simulators.

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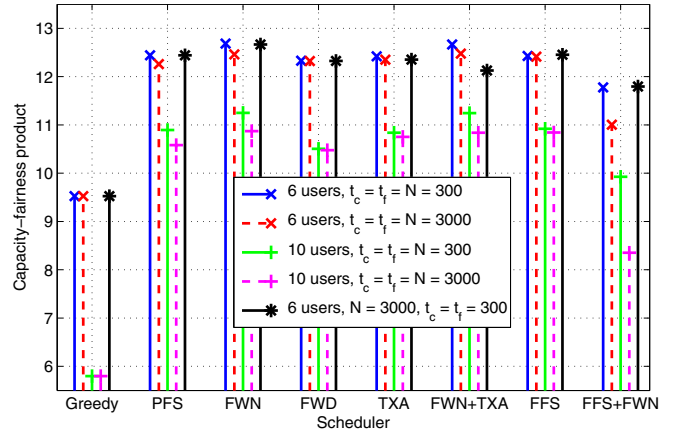


Fig. 7. CFP values for configuration options with $\alpha = \beta = 5$; $\gamma = \delta = 1$.

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